Clinical MRI: From Physical Principles to Practical Protocols

Cardiovascular Methods

Christine H. Lorenz, PhD
Siemens Corporate Research
Baltimore, MD

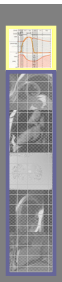
Disclaimers/Disclosures

1. The use of contrast media has not been approved by the FDA for use in Cardiovascular MR. Off label use of contrast media will be discussed in this presentation.
2. The information in this presentation is strictly educational and is not intended to be used for instruction as to the practice of medicine.
3. The speaker is an employee of Siemens Corporate Research

Outline

- Physiology and cardiac MR acquisitions
- Morphology
- Function
- Flow
- Perfusion
- Late enhancement

Outline



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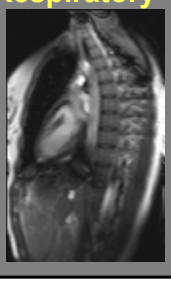
Motion in Cardiovascular MR

Cardiac

Respiratory



Motion Compensation Methods

- ECG Triggering
  - synchronize data acquisition over multiple heartbeats
- Respiratory gating
  - restrict acquisition to quiet periods of cycle
  - breath-holding
- Real time imaging
  - freeze motion

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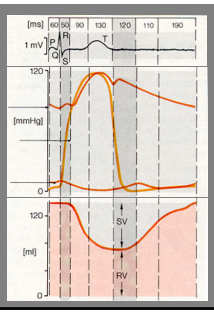
Electromechanical Activity in the Heart



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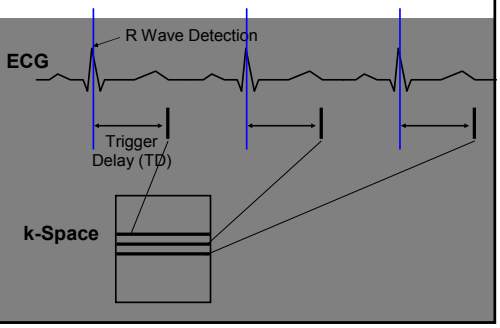
ECG Triggering



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MRI-Related ECG Noise Sources

- B_0 related (main static field)
  - magnetohydrodynamic effect
  - flux change due to motion (respiratory and cable)
- B_1 related (radio-frequency field)
  - RF pulses
  - electrode and ECG amplifier effects
- G related (gradient switching)

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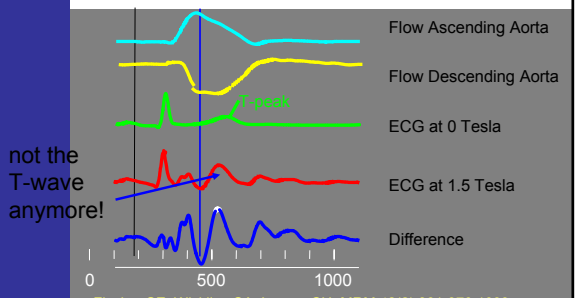
Magnetohydrodyamic Effect (Flow Artifact)



Fischer SE, Wickline SA, Lorenz CH, MRM 42(2):361-370,1999.

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Diagnostic Value of ECG in MR Environment

- Not Diagnostic
  - P-wave, ST-segment, T-wave, T-axis, J-point
  - PQ interval, QT-interval, P duration
- Diagnostic
  - heart rate (accurate QRS detection required, or manual evaluation)
  - electrical axis of the heart
- Heart rate changes due to B_0

Fischer SE et al ISMRM 2000

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Skin Preparation

- Remove chest hair if needed
- Clean and roughen skin surface
  - Remove oil and perspiration to allow better contact of electrodes
  - Clean with abrasive prep pad or gel (NuPrep)
  - **Dry area completely!!!**

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Use MR Compatible ECG Equipment

- MR compatible ECG system
  - Bruker
  - In Vivo
  - Medrad
- MR compatible ECG pads
  - check with MR vendor for recommendation
  - check expiration date
  - do not leave pads exposed to air-will dry out (baseline noise)
- Non MR pads
  - worst case ~ burns
  - RF interference ~ unable to scan!

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Lead Placement Tips: Standard ECG

- The R wave with the highest amplitude will be attained by placing the positive and negative electrodes, **parallel to the electrical axis** of the heart
- The reference electrode can be placed in any position

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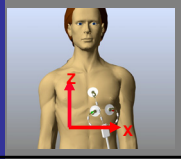
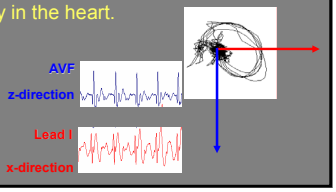
Principle of the VCG (Vectorcardiogram)

- Two-channel ECG system
- Signals from two pairs of electrodes plotted against each other to remove time
- Resulting graph is spatial representation of electrical activity in the heart.





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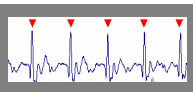
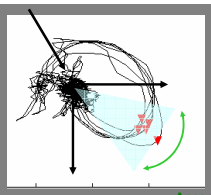
VCG Triggering Principle

Gradient noise, flow artifacts



Magnitude Signal



Acceptance Range

- R-wave is spatially separate from artifacts.
- 2D direction of R-waves is determined during learning-phase, while patient is outside magnet bore.
- Direction information is used to differentiate R-waves from artifacts.

US Patent 5,987,348 SE Fischer, SA Wickline and CH Lorenz

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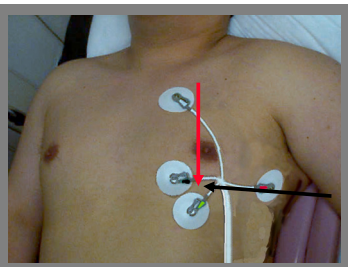
2D VCG Lead Setup Philips Medical Systems



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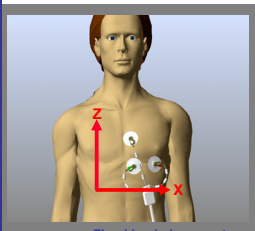
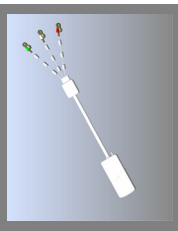
Wireless VCG System Siemens Medical Solutions





Fixed lead placement
Single reference electrode
One vertical lead (AVF), and one horizontal lead (Lead I)

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Summary: ECG Triggering

- Don't start scanning unless ECG is good
- Skin preparation is important for signal quality
- For non-VCG systems, placement of electrodes based on patient characteristics can greatly influence quality of ECG signal

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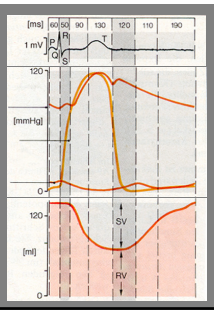
Electromechanical Activity in the Heart



ECG

Pressure (Aortic, LV, LA)

LV Volume

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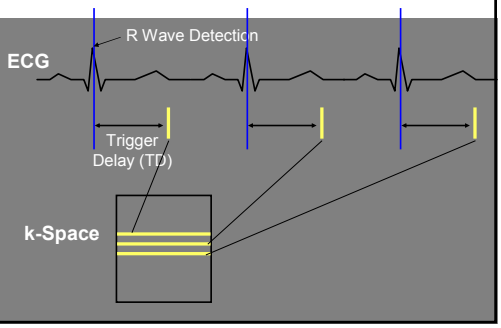
Filling k-space Using ECG Triggering



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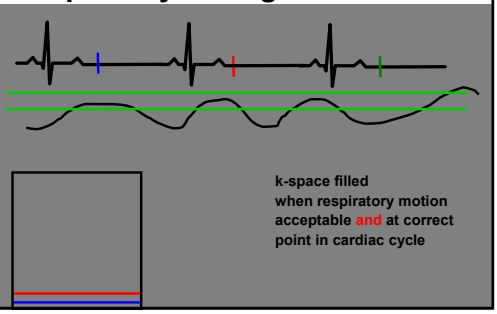
ECG Triggered Acquisition with Respiratory Gating



k-space filled when respiratory motion acceptable and at correct point in cardiac cycle

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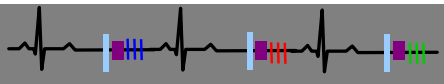
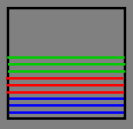
Navigator Gated Imaging Sequences





k-space

- Short acquisition window in diastasis (<100 ms)
- Navigator efficiency 30-50 % heartbeats accepted

Navigator pulse

Fat sat pulse or other contrast enhancing pulse

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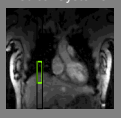
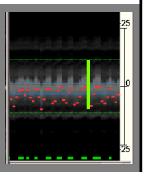
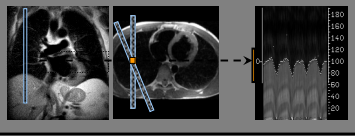
Navigator Technique: Prospective Mode

- Detect respiratory motion
- Accept data only in expiration
- Compensate by adjusting slice position (slice following)

Philips Medical Systems







Siemens Medical Solutions

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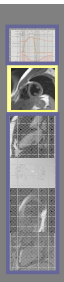
Outline



- Physiology and cardiac MR acquisitions
- Morphology
- Function
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- Late enhancement

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Imaging Heart Anatomy

- Clinical goals
  - Determine relationship between various structures in the heart and in the thorax
  - Identify and characterize tumors, thrombus, fatty infiltration of myocardium, etc
  - Identify and characterize vessel wall abnormalities
- Sequence requirements
  - Good contrast between blood and myocardium
  - Ability to have T1 or T2 weighting to characterize fat, tumors etc.
  - Moderate spatial resolution 1 x 1 mm in plane, 5-7 mm through plane
  - Good suppression of artifacts

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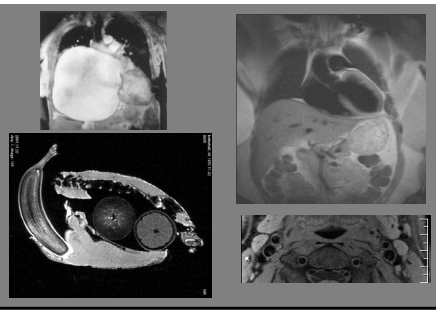
Examples of Anatomic Imaging



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Spin Echo Based Black-blood Techniques

	Spin echo	Turbo spin echo	Haste
Lines acquired per beat	1	8-32	64-128
Temporal resolution	10 – 40 ms	30 –300 ms	200 – 400 ms
Scan time	128 – 384 heartbeats	4 – 32 heartbeats	1 heartbeat

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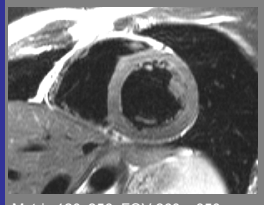
Breath-hold Black-blood Turbo Spin Echo



Matrix 120x256, FOV 260 x 350mm
6mm slice,16 heart beats

- Breath-hold to reduce respiratory artifacts.
- Diastolic gating to reduce cardiac motion artifacts.
- Double-inversion blood effectively eliminates signal from flowing blood.

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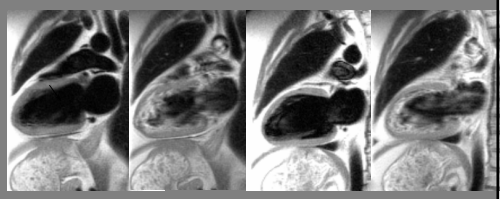
Black-blood Turbo Spin Echo



with without with without

Blood signal artifacts in turbo spin echo can be severe without blood nulling

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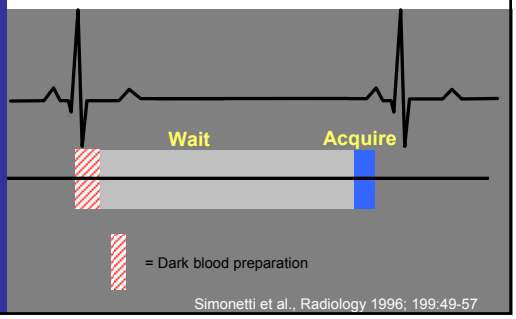
Turbo Spin Echo Black-blood Sequence



Simonetti et al., Radiology 1996; 199:49-57

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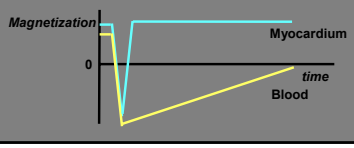
Black-blood Imaging: Preparation

- Spatially non-selective excitation
  - blood and tissue signal inverted
- Section selective excitation
  - tissue signal re-inverted
    - *i.e. no net change in magnetization*
  - systole follows
    - *i.e. blood outside section only sees first pulse*



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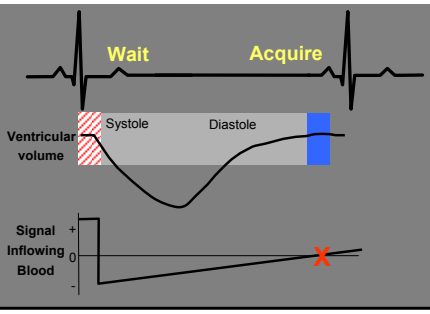
Black-blood Imaging



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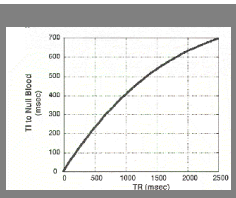
Blood Null Point Varies with HR



Heart Rate BPM	RR msec	Blood Null Point
100	600	400
80	750	530
60	1000	625

Fleckenstein et al., Radiology 1991; 179:499-504

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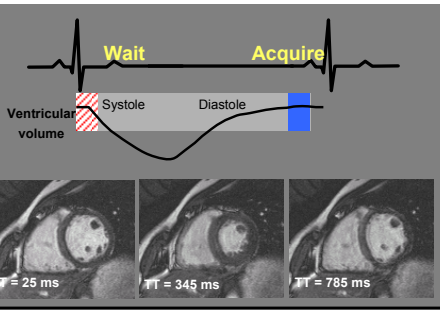
Black-blood Imaging



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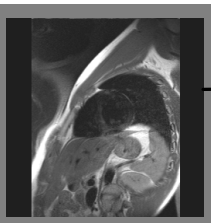
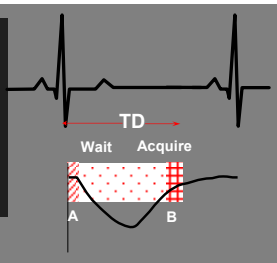
Timing: Delay Too Short





- Slice A ≠ Slice B
- Blood at null point

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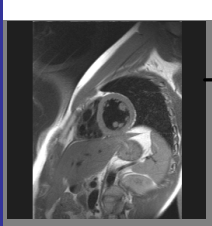
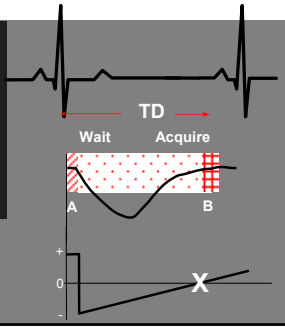
Timing: Delay Just Right





- Slice A = Slice B
- Blood signal zero

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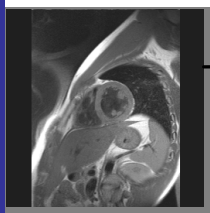
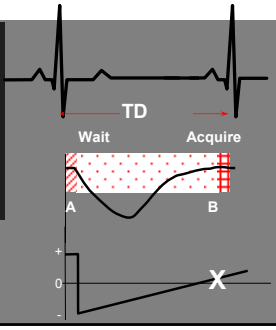
Timing: Delay Too Long





- Slice A = Slice B
- Blood signal recovering

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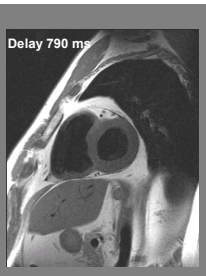
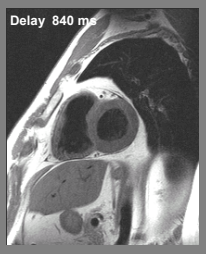
Getting the Timing Right



OK for LV, not for RV



OK for both RV and LV

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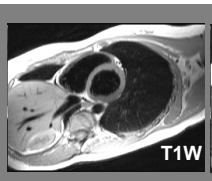
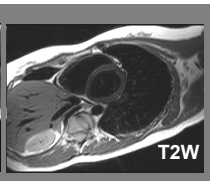
"T1" and "T2"-Weighting





- Short TE values
- Triggering every beat

- Long TE values
- Triggering every other beat

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Variations Of Anatomical Imaging

- White blood single-shot imaging
- Dark blood single shot imaging (HASTE)
- Non-BH spin echo with long TE and no flow compensation
- Contrast enhanced MR angiography

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Outline

- Physiology and cardiac MR acquistions
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Functional Imaging In The Heart

- Clinical goal
  - View and quantitate left and right ventricular function, wall motion, and wall thickening
- Sequence Requirements
  - Moderate spatial resolution (1-2 mm in-plane, 6-8 mm through plane)
  - High temporal resolution (< 50 ms/frame)
  - Suppression of respiratory motion (breathhold, real-time, respiratory gating)
  - High contrast between blood and myocardium

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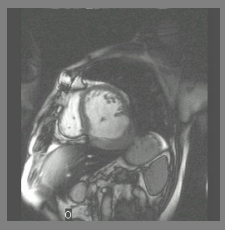
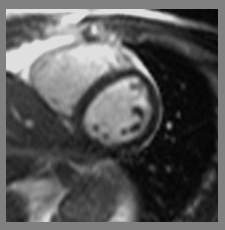
Examples: Functional imaging in the Heart



Standard BH acquisition



Real-time acquisition

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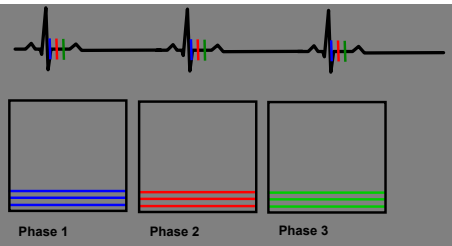
Multiple Phase ECG Triggered Imaging (Cine Imaging)



Example: 3 phases

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Strategies for Shortening Scan Time

- Collect more than one k-space line per phase per beat (segmentation)
- Share collected k-space lines between phases (segmentation with echo sharing)
- Collect fewer lines than in full matrix and use properties of k-space or sensitivity maps to ´fill in´ the rest
  - partial Fourier
  - parallel imaging (SENSE, SMASH, GRAPPA)
  - undersampled radial imaging
- Go really fast…get all lines at once (real time imaging)

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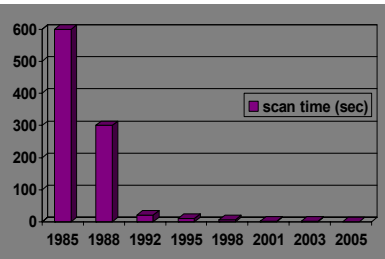
Improvement in Scan Time Cardiovascular MR



functional imaging: time for one cine loop

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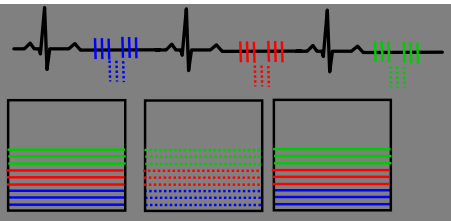
Penalties for Shorter Scan Times

- Less spatial resolution
- Less temporal resolution
- Artifacts

SIEMENS 49

Variations: Segmented Imaging with Echo Sharing

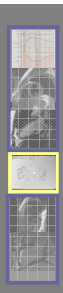


Lines shared to fill k-space of multiple phases

Example: 3 phases

SIEMENS 50

Outline



- Physiology and cardiac MR acquisitions
- Morphology
- Function
- Flow
- Perfusion
- Late enhancement

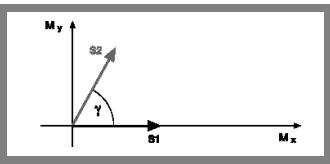
SIEMENS 51

Principle of Phase Contrast Flow Imaging

- Protons moving in the presence of a gradient field produce a phase shift
- The phase shift is directly proportional to velocity
- To compensate for imperfections, flow compensated and flow encoded acquisitions are used in combination

SIEMENS 52

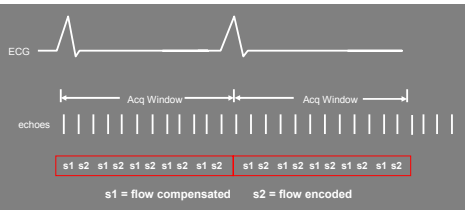
Phase Contrast Technique



- Flow compensated acquisition S1 produces 0 phase shift
- Flow encoded acquisition S2 produces non-zero phase shift
- Difference is proportional to velocity

SIEMENS 53

Interleaved Flow Compensation and Encoding



Velocity (cm/sec) = (γ/180) * VENC
VENC = encoding velocity (cm/s)
Volume flow (ml/sec) = Velocity x Area

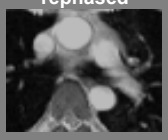
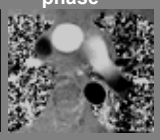
SIEMENS 54

Flow Quantification Cine Sequences

- Retrospective triggering to include entire cardiac cycle preferred
- Temporal resolution depends on number of directions encoded (half of normal cine temporal resolution if 1 direction encoded)
- Same approaches to reducing scan time as for functional cine acquisition can be used (segmentation, parallel imaging, etc)

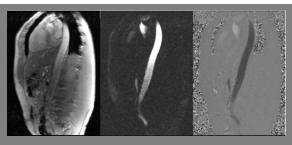
SIEMENS 55

Phase Contrast Cine Images

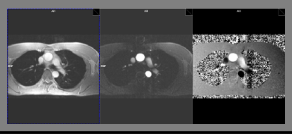
rephased	magnitude	phase
		
magnitude of flow compensated signal S1	magnitude of difference signal S2 – S1	phase of difference signal γ
flow bright background visible	flow bright background suppressed	forward flow bright reverse flow black background midgray

SIEMENS 56

Through-Plane vs In-Plane Encoding of Velocity



In-Plane Sagittal Aorta



Thru-Plane Axial Aorta

SIEMENS 57

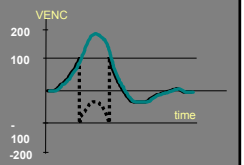
Typical Peak Velocities (cm/sec)

Pulmonary Artery	70-130
Aorta	100 – 175
Carotid Artery	80 – 120
External Iliac Artery	81 – 120
Carotid Syphon	55
Common Femoral Artery	115
Basilar Artery	40
Superficial Femoral Artery	90
Vertebral Artery	40
Popliteal Artery	70
Sagittal Sinus Vein	10
Peripheral Veins	5 – 10

SIEMENS 58

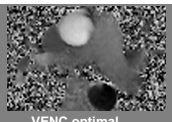
What Happens If The VENC Is Wrong?

- VENC too low
  - aliasing
  - can correct to some extent, recommended to re-acquire with appropriate higher venc
- VENC too high
  - loss of ´velocity´ resolution (poor dynamic range)

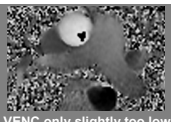


SIEMENS 59

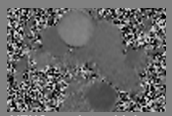
Effect of VENC Selection



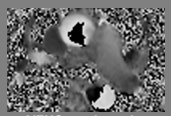
VENC optimal
(max black/white & no aliasing)



VENC only slightly too low
(very little aliasing)



VENC much too high
(washed-out black/white)



VENC much too low
(very much aliasing)

SIEMENS 60

Outline

Physiology and cardiac MR acquisitions

Morphology

Function

Flow

Perfusion

Late enhancement

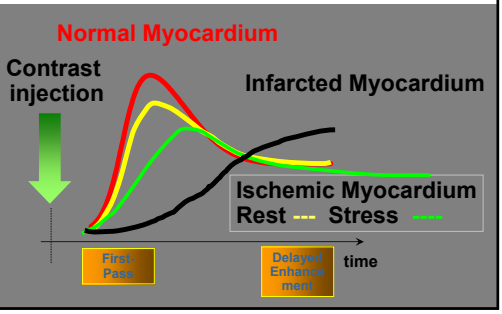
SIEMENS 61

Myocardial Perfusion Imaging

- Clinical goals
  - Detect deficits in blood flow to the heart muscle at rest or under stress
- Sequence requirements
  - At least 1 image per heartbeat per slice
  - Slices to cover relevant segments of the heart (3-5)
  - High T1 sensitivity
  - Good SNR
  - Good spatial resolution (at least 2 x 2 in plane)
  - Resistance to motion artifacts and variations in heart cycle length

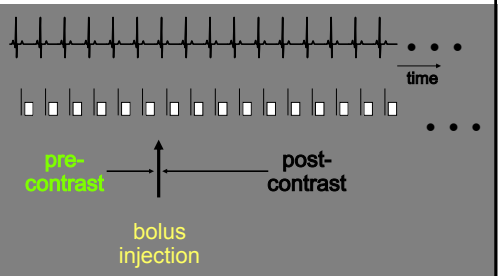
SIEMENS 62

Contrast Enhanced MR



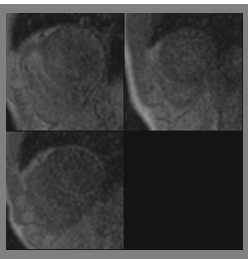
SIEMENS 63

Myocardial Perfusion Imaging



SIEMENS 64

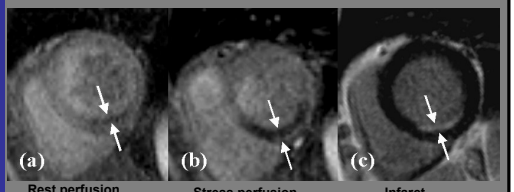
First Pass Myocardial Perfusion



Saturation recovery TurboFLASH with parallel Imaging, GRAPPA rate 2, 1-4 slices/heart beat

SIEMENS 65

Ischemic Heart Disease – Ischemic Region versus Infarct



Rest perfusion | Stress perfusion | Infarct

Sir Run Run Shaw Heart Center, Hong Kong MR0862

SIEMENS 66

Current Pulse Sequences for Myocardial Perfusion with MR

- T1 weighted gradient echo sequences
- Steady State sequences
- Segmented echo planar sequences

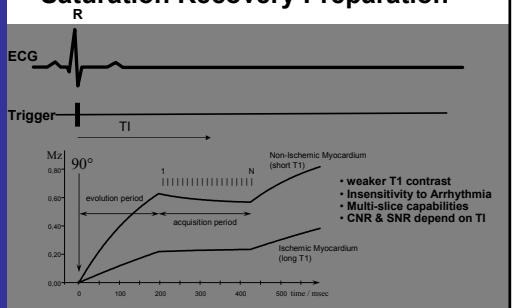
SIEMENS 67

Magnetization Preparation

- Inversion Recovery (180° pulse)
  - Very strong T1 contrast.
  - Multi-slice imaging difficult.
  - Sensitive to arrhythmia.
- Saturation Recovery (90° pulse)
  - Weaker T1 contrast.
  - Multi-slice capabilities.
  - Insensitive to arrhythmia.

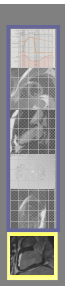
SIEMENS 68

Dynamic First-Pass Perfusion
Saturation Recovery Preparation



SIEMENS 69

Outline



Physiology and cardiac MR acquisitions

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Late enhancement

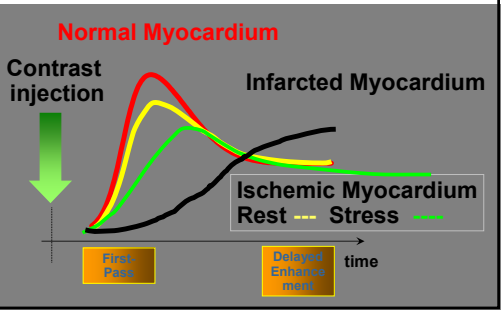
SIEMENS 70

Late Enhancement Imaging

- Clinical goals
  - Identify locations of the myocardium that are 'dead' or injured, including infarcts, fibrous tissue due to myocarditis, intentional ablation, cardiomyopathies, etc
  - Identification from kinetic behavior of Gd-DTPA
- Sequence requirements
  - Highly T1 sensitive
  - High spatial resolution
  - Short acquisition time (obtain images in a BH)

SIEMENS 71

Contrast Enhanced MR

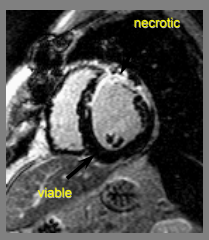


SIEMENS 72

Inversion Recovery Imaging

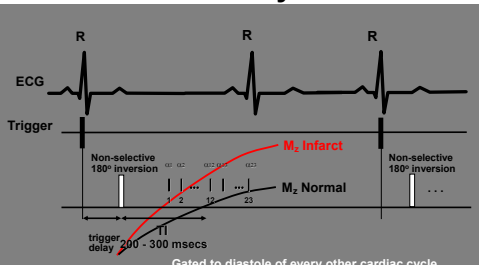
• Shorter T1 of contrast-enhanced infarcted region results in faster signal recovery following inversion.

• Nulling of signal from longer T1 viable myocardium results in maximum contrast ratio.



SIEMENS 73

Basic Imaging Approach: Inversion Recovery

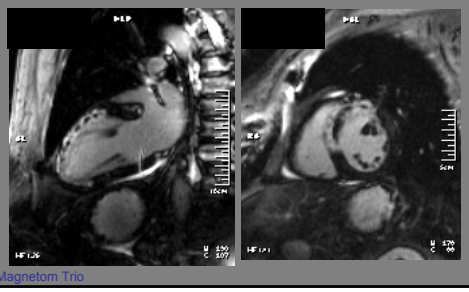


Gated to diastole of every other cardiac cycle.

TI adjusted to null normal myocardium post-Gd.

SIEMENS 74

Late Enhancement Imaging at 3T



Magnetom Trio

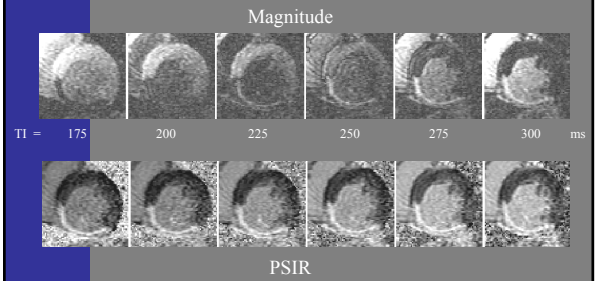
SIEMENS 75

Effect of TI on Image Quality

- Imaging at the null-point of viable myocardium
- TI depends on:
  - Contrast dosage
  - Time between injection and imaging
  - Relaxation time between IR pulses (e.g., 2D versus 3D breathhold imaging)
- And TI is time dependent …
  - Contrast in myocardium washes out with time

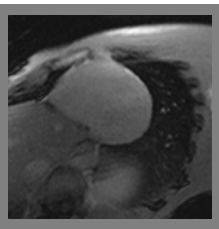
SIEMENS 76

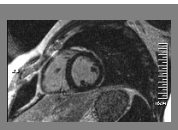
Effect of TI on Late Enhancement Imaging



SIEMENS 77

Inversion Time Scout

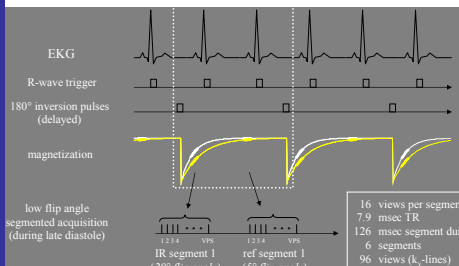




- Inversion Time Scout Sequence
  - Segmented IR-SSFP cine
  - Quickly identify correct inversion time (TI).
  - May be useful for T1 mapping

SIEMENS 78

Phase Sensitive IR Pulse Sequence

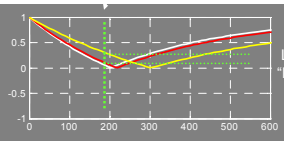


Kellman P, et al, Magn Reson Med. 2002 Feb; 47(2):372-83.

SIEMENS 79

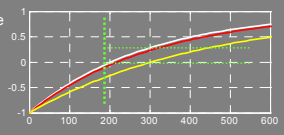
TI Insensitivity of Phase Sensitive IR

Magnitude



Loss-of-Contrast
"Polarity Artifact"

Phase Sensitive



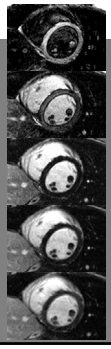
MI
Blood
normal

SIEMENS 80

Phase Sensitive IR

Works over broader range of TI

Magnitude



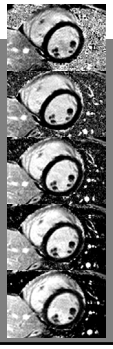
TI = 150 msec too short

TI = 200 msec

TI = 250 msec optimal

TI = 300 msec

TI = 350 msec too long



PSIR

SIEMENS 81

Summary

Physiology and cardiac MR acquisitions

Morphology

Function

Flow

Perfusion

Late enhancement

SIEMENS 82

And for slide contributions…. Thank you!

- Lon Simonetti
- Stefan Fischer
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- Gerhard Laub
- Gary McNeal
- Kevin Johnson
- Carmel Hayes
- Dudley Pennell
- CH Luk